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Detailed stratigraphic, structural, and three-dimensional mapping of the basal surface of the Paleoproterozoic Bravo Lake Formation, Nadluardjuk Lake area, Central Baffin Island, Nunavut

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Abstract: Detailed structural, stratigraphic, and three-dimensional (3-D) geometric characterization of the basal surface of the Paleoproterozoic mafic to ultramafic metavolcanic Bravo Lake Formation has been undertaken southwest of Nadluardjuk Lake, Nunavut. This boundary surface represents a rapid, conformable transition from iron-enriched, siliciclastic, marine deposition (Dewar Lakes Formation) to near-basin-margin, shallow-marine volcanism (Bravo Lake Formation). Deformation style along the basal surface is varied, with tight, upright, east-west trending F_2 folds in the north to localized shear strain in the south. The Bravo Lake Formation is interstratified with an iron-rich volcaniclastic sedimentary unit indicating contemporaneous shallow-water sedimentation and volcanism. The stratigraphic positioning of Dewar Lakes Formation rusty semipelite structurally above younger Longstaff Bluff turbiditic psammite implies tectonic juxtaposition along the boundary of these sedimentary rocks in this region. Geological and geometric constraints from this study can now be used to construct a 3-D volumetric model of this area.

Résumé : Au sud-ouest du lac Nadluadrjuk (Nunavut), on a entrepris une caractérisation détaillée de la géologie structurale, de la stratigraphie et de la géométrie en trois dimensions (3D) de la surface basale de la Formation de Bravo Lake, une unité de roches volcaniques métamorphisées de composition mafique à ultramafique du Paléoprotérozoïque. Cette surface limite témoigne du passage rapide sans discontinuité (contact concordant) d'une sédimentation silicoclastique riche en fer en milieu marin (Formation de Dewar Lakes) à un volcanisme en milieu marin peu profond à la bordure d'un bassin (Formation de Bravo Lake). Le style de la déformation varie beaucoup le long de cette surface; de plis droits P_2, serrés, d'orientation est-ouest au nord, on passe à des zones de cisaillement localisé au sud. Une unité sédimentaire volcanoclastique riche en fer est interstratifiée dans la Formation de Bravo Lake, ce qui indique l'existence d'une sédimentation en eau peu profonde contemporaine du volcanisme. La position stratigraphique des semipélites plus anciennes de couleur rouille de la Formation de Dewar Lakes au-dessus, du point de vue structural, des psammites turbiditiques plus récentes de la Formation de Longstaff Bluff implique une juxtaposition tectonique le long de la limite de ces roches sédimentaires dans cette région. Les limites d'ordre géologique et géométrique établies dans le cadre de cette étude peuvent maintenant servir à la construction d'un modèle volumétrique 3D de cette région.

INTRODUCTION

This study is a follow-up from previous work that examined the possibility of constructing accurate 3-D bedrock models in the Central Baffin region (de Kemp et al., 2001). The main focus of this study is to characterize the basal Bravo Lake Formation contact, to map its exposed 3-D spatial distribution, and to better constrain the Bravo Lake Formation in the Nadluardjuk Lake area within the regional stratigraphic framework (Fig. 1). This will lay the foundation for the construction of a local 3-D structural and stratigraphic model that will potentially contribute to our understanding of regional deformation processes. The 3-D model will also be used as a case study for on-going, in-house, interpretive 3-D tool development, that ultimately will be used in other regional-mapping programs.

Previous investigations in the area have demonstrated that the Nadluardjuk Lake area in Central Baffin Island is underlain by moderately deformed Paleoproterozoic psammitic and semipelitic rocks of the Longstaff Bluff Formation, Piling Group, that appeared to be in tectonic contact with mafic to ultramafic metavolcanic rocks of the Bravo Lake Formation (Corrigan et al., 2001; St-Onge et al., 2001a, b). Field-based validation of the nature of this contact was undertaken at a more detailed scale (1:10 000) in order to verify this hypothesis. From previous work (Corrigan et al., 2001), numerous irregular garnet-muscovite syenogranite bodies were known to crosscut the volcanic-sedimentary contact and, in some cases, were tectonically disrupted in localized strain zones at the contact. In order to examine the Bravo Lake Formation basal surface, a detailed mapping of these intrusive bodies adjacent to, and crosscutting, the boundary was

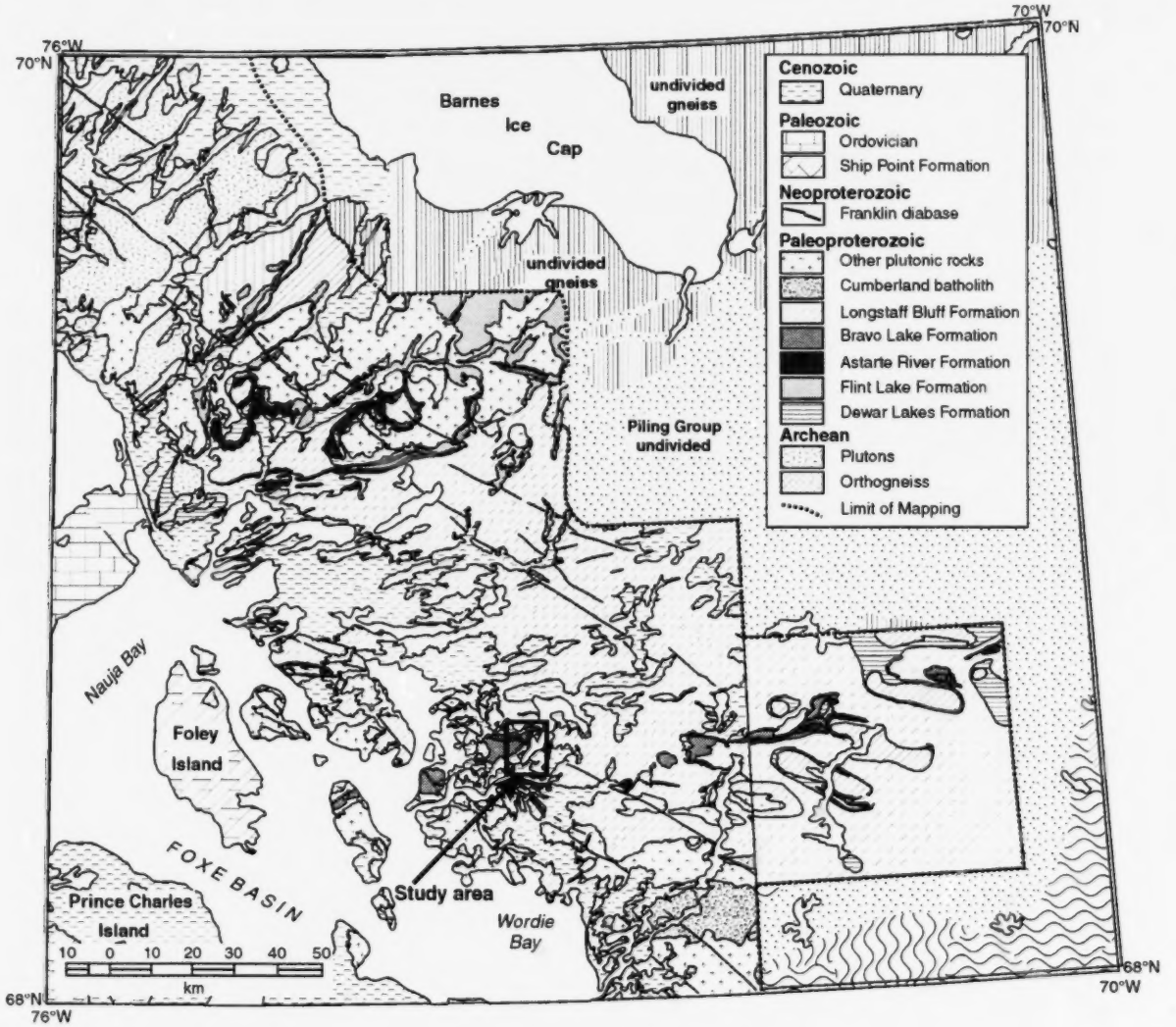

Figure 1. *Location of the 3-D bedrock-mapping study area.*

also necessary. This study thus provided an opportunity to enhance our understanding of emplacement and timing of deformation events in the area, and provide an accurate spatial context for future geochronological and petrological studies (Fig. 2).

The map area is a well exposed, moderately deformed crustal window with topographic relief of 30 to 180 m (m a.s.l.) (Fig. 3). The moderate bedding dips throughout the area (20–40°), when combined with this range of elevation, proved useful in resolving surface geometries of geological contacts. Several relatively accessible cliff exposures that cut through the Bravo Lake Formation basal surface were instrumental in accessing and characterizing the boundary.

3-D BEDROCK MAPPING

Accurate 3-D positioning of geological field data was a requirement of this project, as it would serve as the control for subsequent 3-D modelling. Accuracy of individual field observation sites is estimated to be near 10 and 20 m for horizontal and vertical positioning respectively. Orthorectified airphotos, Global Positioning Systems (GPS), altimeter, and handheld data-capture devices were all used to facilitate the 3-D mapping. Data-entry templates (Gilbert et al., 2001) distributed through the Canada–Nunavut Geoscience Office were modified to accommodate elevation-data entry. Orthophotographs of the map area were derived from black-and-white, 1:33 000 scale, scanned airphotos, geocorrected to a SPOT satellite image and a 1:100 000 scale, stereo, SPOT derived Digital Elevation Model (DEM) (Krupnik, 2000). Slight translation of the orthoimage was required in the field to reflect the more accurate GPS control points that were collected during the course of the field study. These orthophoto base maps were used to extract geographic features such as lakes, streams, escarpments, and topographic peaks that could be used to reference data, and interpretations made during field traversing of the area. Daily outings involved plotting of detailed observation sites and contact information on high-resolution 1:10 000 scale field slips. These field slips contained the topographic information extracted from orthophotographs and grid co-ordinates, and was used to plot geological features using GPS positioning. Recording of more detailed descriptive information was done in hardcopy notebooks. From the fieldwork, geological and topographic control points all had X, Y, Z geopositioning that could be used to develop a new high-resolution topographic model (Fig. 3). This topographic surface was used for direct interpretation and positioning of geological contacts by on-surface digitizing in 3-D, or to elevation-correct the geological contacts as interpreted from the 2-D map pattern. The compiled digital field data from this summer's work consisted of accurate X-, Y-, Z-attributed site information for interpreted geological boundaries and accurate geopositioning, rock classification and descriptions, structural observations, sample sites, and photograph locations.

SOFTWARE TOOLS

Visualization and interpretation of the bedrock field data was done with a combination of standard and enhanced software tools in ArcView® 2-D GIS, gOcad 3-D modelling software, and ER Mapper image-processing tools, on a laptop PC. The enhanced program extensions were used for specific 3-D conversions and manipulations including advanced geometric-property interpolations and surface construction. Specifically, these include ArcView 3.2 extensions to facilitate smooth transfer from Pendragon field-data capture software to ArcView (Palm2AV.avx) and interactive plotting of structural data (3dgeo.avx). Plug-ins for gOcad, developed at Mira Geosciences and the GSC, (Mira Tools plug-in and Sparse Data plug-in respectively) are used to import point and line data (ESRI shape format) and export structural and topographic contours (DXF format) from 3-D surfaces. Collectively these tools acted as a 3-D geographic information system (GIS) that could effectively query for specific field-based information, link it with geospatial objects such as a geological boundary, and represent it in 3-D. The results from 3-D manipulations, such as contour extraction from the constructed 1:10 000 scale topographic surface, could then be exported back to 2-D GIS for plotting on detailed field slips.

GENERAL GEOLOGY

The map area is within the Trans-Hudson Orogen of Central Baffin Island (Fig. 1) in the east-west-trending Foxe Fold Belt (Jackson, 1969, 1978; Morgan et al., 1976). The southwest Nadluardjuk area contains exposed bedrock previously interpreted as part of the allochthonous northeastern boundary of the Bravo Lake Formation (Corrigan et al., 2001). These dominantly mafic to ultramafic metavolcanic rocks are surrounded by semipelitic and psammitic metasediments of the Dewar Lakes and Longstaff Bluff formations, respectively. The dominantly metavolcanic Bravo Lake Formation and quartzitic Dewar Lakes Formation form an associated assemblage in this map area and beyond, to the east and west, in various outliers and klippen (Scott et al., 2002). The northern margin of the Foxe Fold Belt, outside the map area, is composed of reworked Archean basement (Rae Province); a thin unconformably overlying parautochthonous lower sequence of quartzite and marble (Dewar Lakes and Flint Lake formations, respectively, of the Piling Group), and an upper foredeep sequence (Astarte River and Longstaff Bluff formations). A metamorphic-plutonic zone dominated by psammitic migmatite and granitoid of the Cumberland batholith bounds the southern edge of the Foxe Fold Belt and is located at the southern edge of the map area. The dominant deformation in the map area is a composite of three Paleoproterozoic deformation events. An early thrusting and localized transposition event (D_{1P}), an event producing east-west-trending upright to slightly overturned tight folds (D_{2P}), and a cross-folding (D_{3P}) event that produces east-west elongated type 1 interference structures (Ramsay, 1967) that form regional-scale basement-cover culminations.

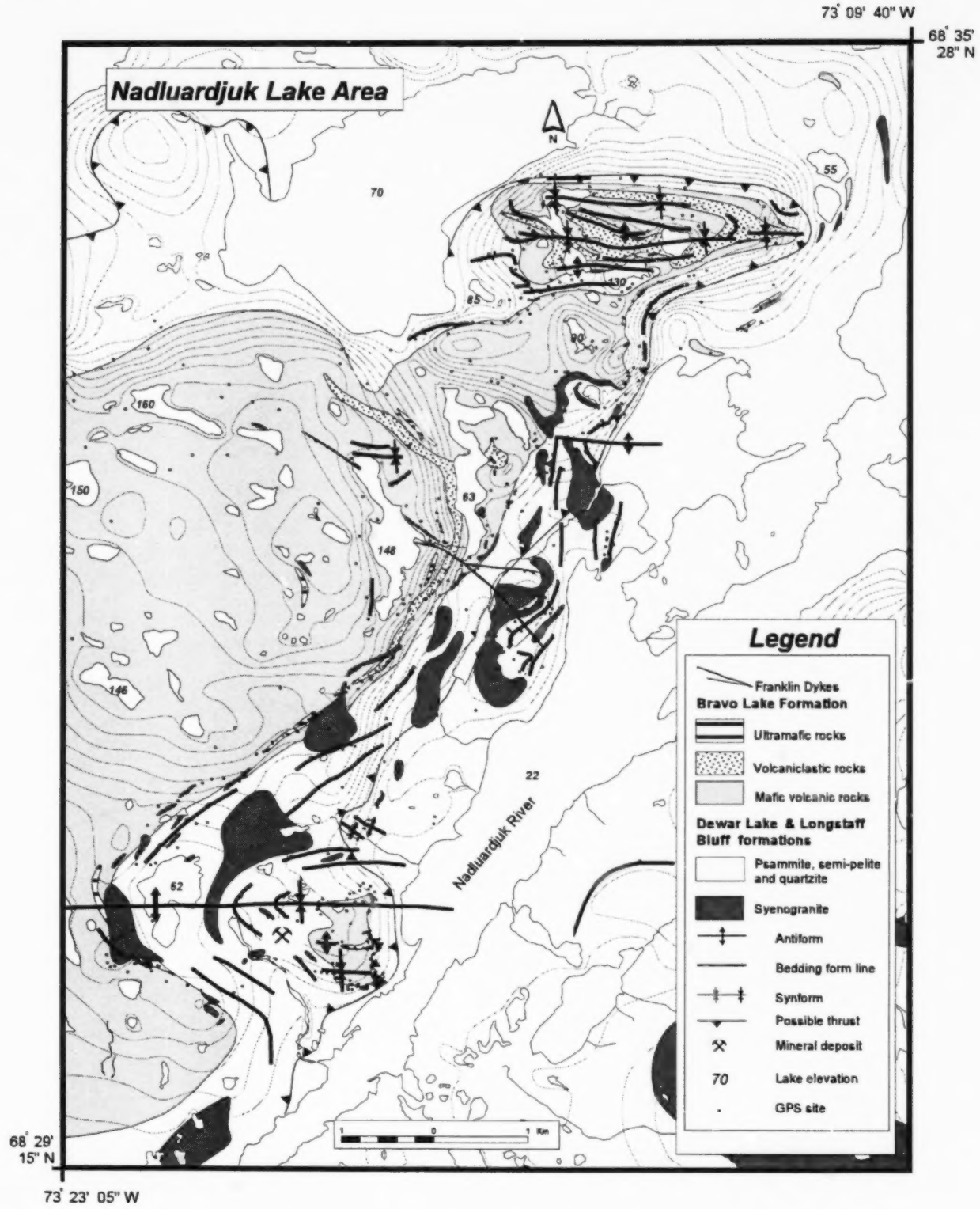

Figure 2. *Bedrock geology of the southwest Nadluardjuk Lake region.*

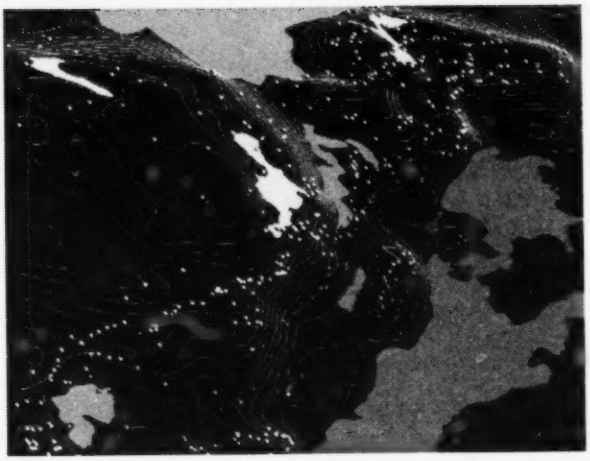

Figure 3. *Virtual perspective view of digital elevation model of the map area. View looking northeast from 1000 m altitude. Contour interval 10 m. Balls represent GPS control points.*

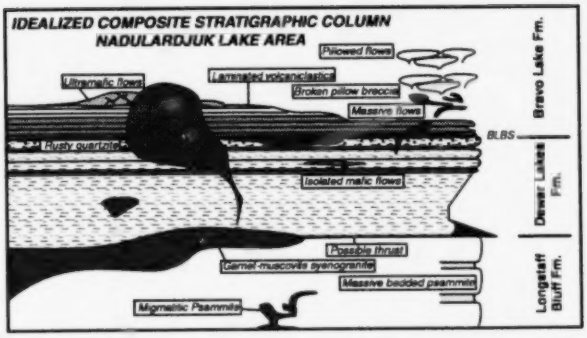

Figure 4. *Idealized composite stratigraphic column for southwest Nadluardjuk Lake area.*

Figure 5. *View looking southwest in the centre of the map area. Rightmost cliff exposures are Bravo Lake Formation mafic metavolcanic rocks. Foreground is underlain by Dewar Lakes Formation rusty semipelite, intruded by garnet-muscovite syenogranite sills. Granite sills tend to form resistant caps to hills.*

STRATIGRAPHY

The Paleoproterozoic stratigraphic record in the Nadluardjuk region records a conformable transition from shallow submarine siliciclastic sedimentation (Dewar Lakes Formation) to near-shelf mafic/ultramafic and minor andesitic volcanism (Bravo Lake Formation). This transition assemblage is likely to have been structurally imbricated with younger turbiditic psammite units of the Longstaff Bluff Formation to the north and east of the map area. Most of the attention of this study was at the transition Bravo Lake Formation basal surface contact (Fig. 4).

The Bravo Lake Formation basal surface was difficult to characterize geologically as this surface is often masked by crosscutting garnet-muscovite syenogranite sills and dykes (Fig. 5). Locally, where exposed, the surface is characterized by a sharp conformable contact with massive to layered mafic flows overlying a rusty meta–quartz wacke, or by a diffuse rusty fissile zone that mask original lamination and bedding characteristics. Sediments directly below the surface are generally semipelitic and interbedded with 2 to 10 cm thick psammite. Fine-scale lamination in the semipelite is occasionally contorted with crosscutting 1 to 3 mm wide pyrite veinlets and disseminated sulphides throughout (Fig. 6). Medium-grained quartzofeldspathic metawacke beds, up to 3 m in thickness, occur at or a few metres below the Bravo Lake Formation basal surface in several locations. These distinctive light beige and smooth-weathering units are similar in composition to Dewar Lakes Formation quartzitic metasediments throughout the region. A similar association of quartzite with mafic metavolcanic rocks and amphibolite has been observed to the east, near Dewar Lakes (Henderson et al. 1988, 1989; Henderson and Henderson, 1994; Scott et al., 2002). Also, a local occurrence of rusty quartzose semipelite

Figure 6. *Intercalated rusty semipelite and mafic epiclastic rocks at base of Bravo Lake Formation. Note crosscutting pyrite veinlets through semipelite.*

within the lower Piling Group stratigraphy, (Flint Lake Formation marble and Dewar Lakes Formation quartzite) near Flint Lake (St-Onge et al., 2001c) to the north, has been observed (M.R. St-Onge, pers. comm., 2001; Scott et al., 2002). This regional association suggests that Dewar Lakes and Bravo Lake formations record an essentially conformable transition of basin-margin siliciclastic deposition to shallow-marine mafic and ultramafic volcanism in this southern part of the Rae margin, and to platformal carbonate deposition along the northern part of the Rae margin. Essentially, the Flint Lake Formation carbonate units and Bravo Lake Formation metavolcanic rocks may be chronostratigraphic equivalents.

Sedimentary rocks more characteristic of the Longstaff Bluff Formation occur tens to hundreds of metres structurally below the Bravo Lake Formation basal surface throughout the map area (Fig. 7a). These sedimentary rocks are characterized by thick psammite to semipelite beds, with coarser massive psammite beds several metres in thickness. By contrast, rocks structurally overlying and near the surface are more heterogeneous, have finer bedding and lamination, and have more of a pelitic (biotite-hematite) component (Fig. 7b). The Longstaff Bluff psammite also occurs as enclaves or border entrainments within syenogranite plutons.

The nature of the upward transition of Longstaff Bluff metasediments structurally below the upper Dewar Lakes Formation semipelite is not yet clear. As this transition would reflect an upward progression from what are younger rocks to older rocks, it is possible that a tectonic break, such as a thrust, could account for this juxtaposition. Recognition of thrust surfaces in ancient metasedimentary terrain is extremely difficult (Price, 1992), and in more recent orogenic belts they are often inferred from stratigraphic arguments alone. Further study is warranted to either locate the actual tectonic surface break or to compare the detrital age signatures in the two juxtaposed sediments.

In the Nadluardjuk Lake area, Bravo Lake Formation rocks are dominantly composed of massive to blocky pillowed mafic flows. Infilling of pillow shelves, vesicles, and pillow junctions with metacarbonate is common (Corrigan et al., 2001). Rare metacarbonate interbeds, 5 to 10 cm in thickness, have been observed. Near the Bravo Lake Formation basal surface, flows tend to be several centimetres in thickness with little flow-boundary disruption (Fig. 8). Pillows at that location tend to be small (< 50 cm). Mafic metavolcanic pillow breccia and fragmental debris deposits are common, often exposed as weathered, rough, blocky surfaces. A rusty, quartzose semipelite is present within the Bravo Lake Formation, approximately 25 to 75 m upsection from the basal surface (Fig. 9). It appears to pinch out laterally where it is characterized by an increase in finer intermediate volcaniclastic debris or ash, and locally by an increase in sulphide mineralization and characteristic rusty weathering (Fig. 10). Localized, rusty pyrite-hematite zones transect both the basal surface and the base of the Bravo Lake Formation sedimentary unit at a high angle, indicating that sedimentary and volcanic lithologies were in contact prior to this mineralization event. The unit

Figure 7a. *Typical massive interbedded psammite of the Longstaff Bluff Formation. Photo looking north.*

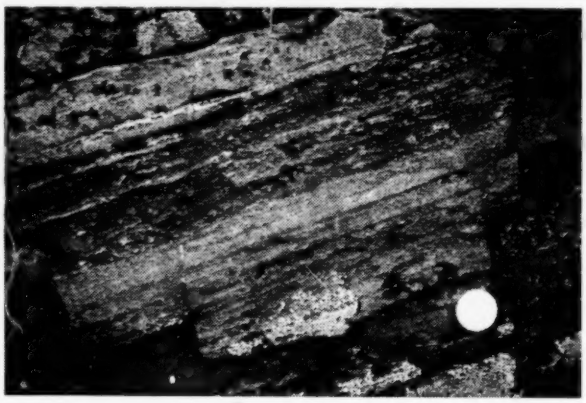

Figure 7b. *Finely laminated and centimetre-scale, interbedded, garnet-bearing quartzofeldspathic metawacke or semipelite typical of metasedimentary rocks in Dewar Lakes Formation, just below the basal metavolcanic rocks of the Bravo Lake Formation.*

Figure 8a. *Bravo Lake Formation thinly banded mafic metavolcanic flows. Negatively weathered ridges are fine-grained recrystallized hyaloclastite at cooling surface of flows.*

Figure 8b. *Close-up of finely laminated and banded mafic metavolcanic rock depicted in Figure 8a. Note angular mafic fragment within individual flow.*

Figure 8c. *Mafic flow breccia and pillow breccia, Bravo Lake Formation. Width of photo approximately 1 m.*

Figure 8d. *Bravo Lake Formation, irregular fine-grained, brown banding in massive mafic metavolcanic flow. Possibly the result of incorporation of underlying rusty semipelite.*

Figure 9a. *Bravo Lake Formation volcaniclastic member. Mafic to intermediate tuffaceous beds interbedded with iron-rich siliciclastic semipelite depicted in Figure 9b.*

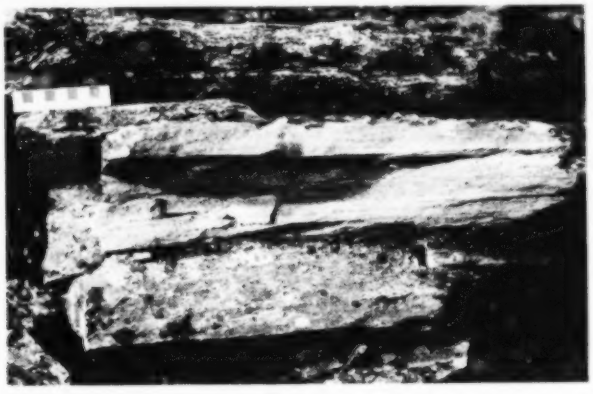

Figure 9b. *Bravo Lake Formation, close-up of individual semipelite bed from cliff face depicted in Figure 9a. Note iron staining and fine millimetre-scale lamination within 2 to 5 cm scale beds.*

contains thinly bedded (1–5 cm thickness), highly fissile epiclastic rocks that are dark grey to light brown on weathered surface. These rocks have fine internal fabrics defined by millimetre-scale, alternating mafic and felsic lamination (biotite-plagioclase±hornblende and quartz-plagioclase) (Fig. 9b). A pinch-out of this unit was mapped along a 30 m wide channel-fill within massive mafic flows. This unit is as yet unnamed and an intermediate tuffaceous bed has been sampled from it for U/Pb geochronology (Natasha Wodicka, pers. comm., 2001).

Several massive ultramafic bodies, less than 20 m in thickness, outcrop near the aforementioned volcaniclastic units (Fig. 2). Ultramafic metavolcanic rocks display a 'ghost' polysuturing structure, with 20 to 100 cm long tremolite-serpentinite fibres along joint faces. They are associated with a mix of blocky, massive, and thinly bedded mafic metavolcanic flows.

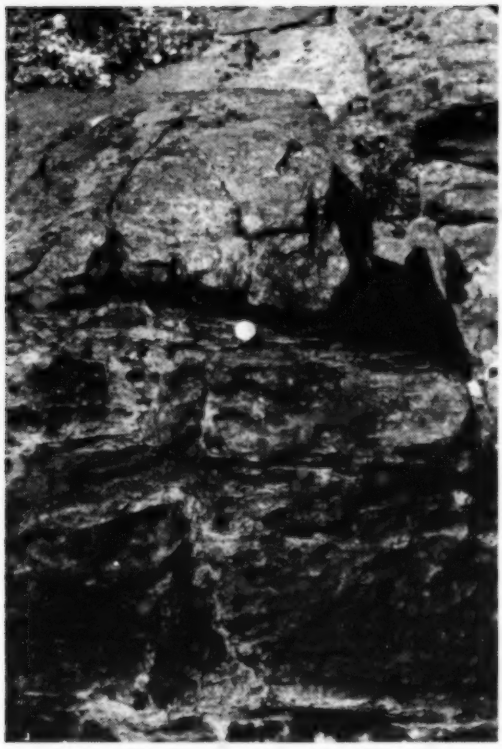

Figure 10a. *Extensively pyritized Bravo Lake Formation basal surface, conformable contact, with mafic metavolcanic flow of Bravo Lake Formation, above coin in centre of photo, and semipelite Dewar Lakes Formation, below coin. Note numerous crosscutting fractures and almost complete masking of primary bedding fabric in semipelite.*

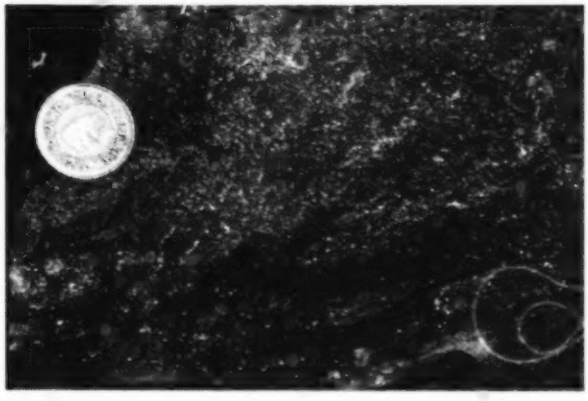

Figure 10b. *Fresh surface of quartz-rich semipelite (quartz-wacke) with numerous mineralized veinlets and disseminated sulphides, Bravo Lake Formation volcaniclastic member.*

Muscovite (± garnet) syenogranite outcrops extensively throughout the map area. Sills, small plug-like bodies, and larger crosscutting dykes are intruding the Bravo Lake Formation basal surface from the north to the south of the map area (Fig. 2). Partial melting in the Longstaff Bluff Formation in the south of the map area may provide a possible source for these S-type intrusions. From the map pattern, there appears to be a selective preference for sills to intrude along the Bravo Lake Formation basal surface and other minor lithological boundaries. The masking of the basal surface and possible lower thrust contacts (Dewar–Longstaff formations boundary) by these granite bodies is a hindrance to establishing clear stratigraphic and structural relationships. Nevertheless, strategic examination of relict enclaves and contacts outside the areas affected by the intrusions is possible in this area.

STRUCTURAL GEOLOGY

Preliminary structural investigation of the unmasked portions of the Bravo Lake Formation basal surface indicates a range of strain styles affecting the rocks at this boundary. One end-member style is characterized by an increase in penetrative platy fabric (S_0/S_1) at the contact, and appears to be localized into heterogeneous, anastomosing, centimetre-scale shear zones which wrap around granitic sills. Occasionally, centimetre-thick quartz-biotite-hematite (± grunerite) pelite beds form anastomosing fabrics around more resistant quartz-rich psammite. Localized dissection through boudinage and rotation of these psammitic beds is not consistent, and angular rotation of inclusions is low (<20°). Lineations associated with these zones are often subtle, quite variable, and not penetrative, suggesting they are more a result of adjacent surface flexural slip than bulk extension. Narrow granitic sills and dykes in these zones can be boudinaged, slightly rotated, and locally isoclinally folded. A mixed lithological assemblage interpreted as a potential tectonic mélange (Corrigan et al., 2001; Raymond, 1975) at the basal surface, in the southern part of the map area, appears to be monolithic and has up to 1 m sized boudinaged granite inclusions demonstrating consistent dextral rotation with top-to-the-northeast sense of shear. This may indicate localized late (syn- to postintrusive) thrusting or listric motion along parts of the basal surface. Angles between volcanic flow contacts and the basal surface are high in one of these areas and may be a result of local block rotation adjacent to a tectonic slip surface.

The second end-member deformation style can be observed at several locations along the length of the Bravo Lake Formation basal-surface map trace. At these locations, massive or pillowed mafic flows lie conformably on quartzitic semipelite or more massive quartz-wacke. These locations show little or no shear strain at the contact surface and tend to be less rusty. The basal surface in these areas tends to undergo rotational strain within the steepened limbs of tight F_2 interference folds (Fig. 11). Occasional high angles (15–25°) between conformably overlying mafic metavolcanic flow

Figure 11. Shallow, west-plunging F_2 fold nose in Bravo Lake Formation quartzose semipelite. East side of Crown Lake looking west.

boundaries and the basal surface have been observed near epiclastic channel fills, possibly indicating steep local paleoslopes.

Syenogranite has been observed to cut composite S_0/S_1 fabrics along the Bravo Lake Formation basal-surface contact. Boudinaged components of crosscutting syenogranite sills are also internally foliated, indicating either two fabric-forming events or a protracted deformation during sill emplacement along parts of the basal surface. Granitic sheets and sills throughout the basal surface are folded along upright, open, northwest-southeast F_3 folds. Crosscutting fracture cleavage associated with F_3 folds is common. The broad warping by F_3 folds results in re-rotation of tight, shallow, F_2 fold hinges from near horizontal to 15 to 20° east-west trends. Antiform-synform inflections occur at several places in the map area as a result of the F_2-F_3 interference pattern. The overall pattern of folding along the Bravo Lake Formation basal surface should become more apparent as the 3-D model is constructed.

DISCUSSION

This field study demonstrates the capacity for addressing regionally significant geological problems by conducting targeted high-resolution mapping. Stratigraphic and structural issues such as the delineation of a tectonic versus a stratigraphic boundary can have an impact on the wider regional interpretation. One of the goals of the 3-D component of the 4-D geoscientific study of Central Baffin Island is the construction of regional 3-D bedrock geology models, or what is referred to as 3-D bedrock maps (de Kemp, 2000a, b) or 'common earth models' (McGaughey, in press; McGaugey and Morrison, 2001). These 3-D models are block models that extend the surface geology upwards and downwards a distance that gives a new dimensionality to the geological map. In similar fashion to extending 2-D curvilinear map traces by geological interpretation, complex 3-D curved surfaces are extended beyond the observed erosion surface. The construction of these 3-D maps is extremely time consuming, and, as with the construction of a 2-D map, is highly interpretive. Enhancing the environment for making these interpretations both in 2-D and in 3-D is the goal of modern geoscience integration. Establishing case studies with associated data sets such as the 3-D data collected in this study is key to developing new tools that optimize the geological interpretive process. From this field study, high-resolution 3-D field data now exists for this area. By integration of our data with the updated regional stratigraphic model (Scott et al., 2002), we will attempt to apply recently developed methods (de Kemp and Sprague, 2001) to construct a 3-D model which will be reported on at a later date.

CONCLUSIONS

The Bravo Lake Formation basal surface in the Nadluardjuk Lake area is a conformable stratigraphic contact that has been locally disrupted by moderate shear strain and rotation through interference folding. However, based on lithostratigraphic evidence, a regional-scale tectonic break may exist lower in the metasedimentary sequence between upper-deck, older Dewar Lakes Formation quartzose semipelite, and lower-deck younger Longstaff Bluff metapsammite.

It appears that the potential chronostratigraphic equivalence between Bravo Lake and Flint Lake formations can provide a useful regional geological datum that combines to form a marker surface where these units are in contact with the top of the Dewar Lakes Formation. This marker surface could be used to connect 3-D model elements from the northern (Flint Lake area) to the southern (Nadluardjuk Lake area) portions of the Rae margin of the Trans Hudson Orogen.

These conclusions complement results from other bedrock mapping projects in the region (Scott et al., 2002) and demonstrate that targeted high-resolution field mapping can be a useful complement to broader based mapping programs.

This study benefited from the use of high-resolution orthoimage base maps created from scanned airphotos, 10 to 15 m accurate 3-D GPS and Palm-based data capture (Gilbert et al., 2001). These products provide a reasonable visual reference for detailed field-data capture in preparation for 3-D modelling. In the future, such a study would benefit from higher quality interpretive image maps such as that provided by hyper spectral imagery (Harris et al., 2001), and a more detailed digital topographic base. It is expected that the benefits from targeted bedrock field studies will increase as the accuracy and predictive methodologies of these technologies continues to improve.

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